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Abstract: In some semiconductors there is strong coupling between lattice waves and free electrons due to the piezoelectric effect. This coupling provides an energy-exchange mechanism from the electron system to the lattice system. This transfer is experimentally observed here as the amplification of an ultrasonic wave and as an "acoustoelectric" current resulting from the wave-electron drag. Experimental results are presented which support an acoustoelectric-effect explanation of a "kink" in the current-voltage characteristics of piezoelectric semiconductors.

Introduction

In high-purity semiconductors the mobility of the carriers can be explained in terms of electron scattering by lattice vibrations (phonons) alone. For carrier interactions with acoustical phonons in Ge and Si, Bardeen and Shockley[1)] have developed the "deformation potential" method of calculating this scattering, yielding the familiar $T^{-3/2}$ temperature dependence of mobility. In their model a deformation produces a change in the energy of the band edge. For piezoelectric semiconductors, such as ZnO and CdS, the

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* Based in part on a thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering at Massachusetts Institute of Technology.

1) J. Bardeen and W. Shockley, Phys. Rev. 80, 72 (1950).

the scattering of carriers by acoustical phonons is a consequence of the piezoelectric fields accompanying the lattice vibrations. In the "piezoelectric field" model of the scattering, the deformation produces an electric field. The piezoelectric scattering mechanism has been used to explain the temperature dependence of mobility and the Seebeck effect in ZnO and CdS with some success by Hutson[2)] and in CdS by Zook and Dexter.[3)] The temperature dependence of the mobility calculated by this model is $T^{-1/2}$.

The "deformation potential" coupling and the "piezoelectric field" coupling are similar in that they both provide an energy-exchange mechanism between the lattice and the free carriers. The former has been discussed by several authors[4-8)] in terms of the interaction between free carriers and long-wavelength acoustical phonons in the form of traveling ultrasonic waves. Weinreich et al.[6)] have experimentally used the mechanism to determine the intervalley-scattering rate in n-type germanium, and Dumke and Haering[7)] used it to explain ultrasonic-wave amplification in semimetals.

The "piezoelectric field" coupling has recently been used by Hutson et al.[9)] to explain both the attenuation of an ultrasonic wave proportional to the carrier concentration and, under appropriate conditions, the possibility of transferring energy from the carriers to the ultrasonic wave. It is this energy exchange that will be discussed in the remainder of this paper. A more complete treatment of the coupling than that given by Hutson is provided by

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2) A. R. Hutson, J. Appl. Phys. 32, 2287 (1961).

3) J. D. Zook and R. N. Dexter, Phys. Rev. 129, 1980 (1963).

4) R. H. Parmenter, ibid. 89, 990 (1953).

5) G. Weinreich et al., ibid. 104, 321 (1956).

6) G. Weinreich et al., ibid. 114, 33 (1959);

7) W. P. Dumke and R. R. Haering, ibid. 126, 1974 (1962).

8) H. N. Spector, ibid. 127, 1084 (1962).

9) A. R. Hutson, J. H. McFee, and D. L. White, Phys. Rev. Letters 7, 237 (1961); A. R. Hutson and D. L. White, J. Appl. Phys. 33, 40 (1962).

White.[10]

Hutson's experiments involved the propagation of a high-frequency ultrasonic wave through a bar of CdS. The free carriers were drifted by a d-c field in the direction of wave propagation. When the drift velocity of the carriers equaled the ultrasonic-wave velocity, there was no energy exchange between the carriers and the ultrasonic wave. For drift velocities greater than the wave velocity, energy was coupled from the carriers to the wave, resulting in its amplification. For drift velocities less than the wave velocity, the wave gave up energy to the drifting electron stream.

The effects to be considered here are all results of this piezoelectric energy-exchange mechanism. The first of these is the experimentally observed amplification of an ultrasonic wave propagating through the piezoelectric semiconductor CdS. The second is the drag exerted by the ultrasonic wave on the carriers. This effect, described as the "acoustoelectric effect" by Parmenter[4] and investigated by Weinreich[6] and Wang,[11] arises for much the same reason that driftwood moves toward the shore. It results in a d-c current component in the direction of wave propagation. This acoustoelectric current will be used here to explain the observed kink in the current-voltage characteristics of piezoelectric semiconductors reported by Smith.[12] Experimental results are given to support the analysis of Hutson.[13]

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10) D. L. White, J. Appl. Phys. 33, 2547 (1962).

11) W. Wang, Phys. Rev. Letters 9, 443 (1962).

12) R. W. Smith, ibid. 9, 87 (1962).

13) A. R. Hutson, ibid. 9, 296 (1962).

I. Amplification of Ultrasonic Waves

A. Experimental Arrangement and Observations

The piezoelectric coupling through which an ultrasonic wave can exchange energy with the free electrons in a semiconductor was observed in a specially constructed sample holder (Fig. 1). In it a pulsed ultrasonic wave can be introduced into a piezoelectric semiconductor parallel to an applied d-c electric field. The sample holder has two transducers: one for transmitting a pulsed ultrasonic signal and the other for receiving the signal after it has passed through the semiconductor. The drift-field terminals serve to apply the d-c electric field to the sample in order to drift the electrons parallel to the ultrasonic wave.

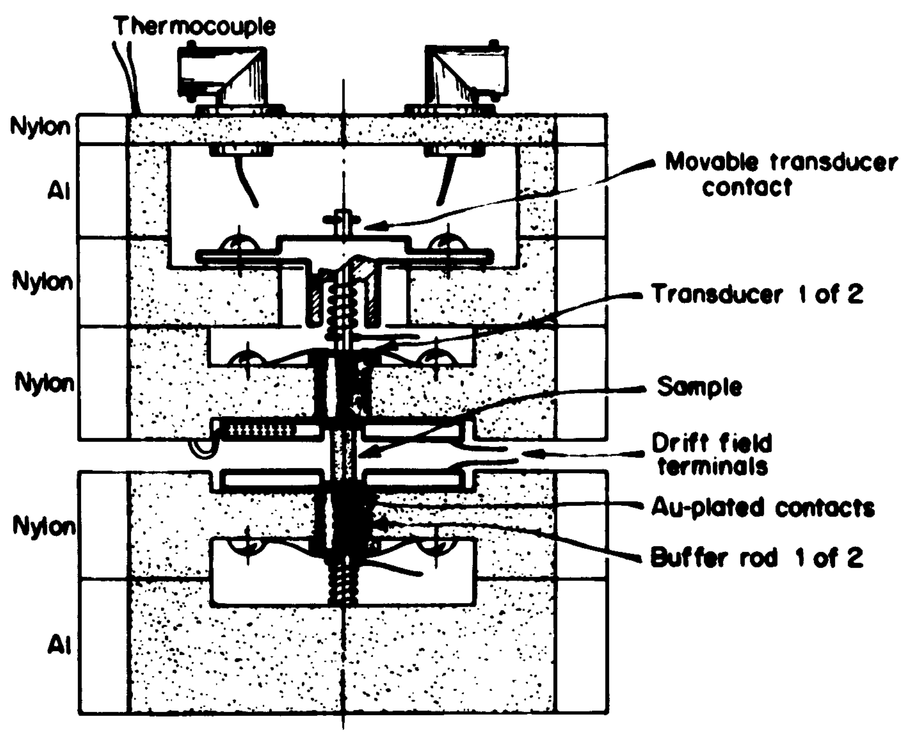

Fig. 1. Full-scale front view of the sample holder.

The piezoelectric semiconductor cadmium sulfide was chosen because of its relatively high electromechanical coupling coefficient and its availability in large crystals. The crystal used here had a dark resistivity $> 10^8$ ohm-cm and an electron mobility of ~ 165 cm^2/volt-sec when illuminated. The free electrons were photoexcited using the weakly absorbed yellow lines of sodium.

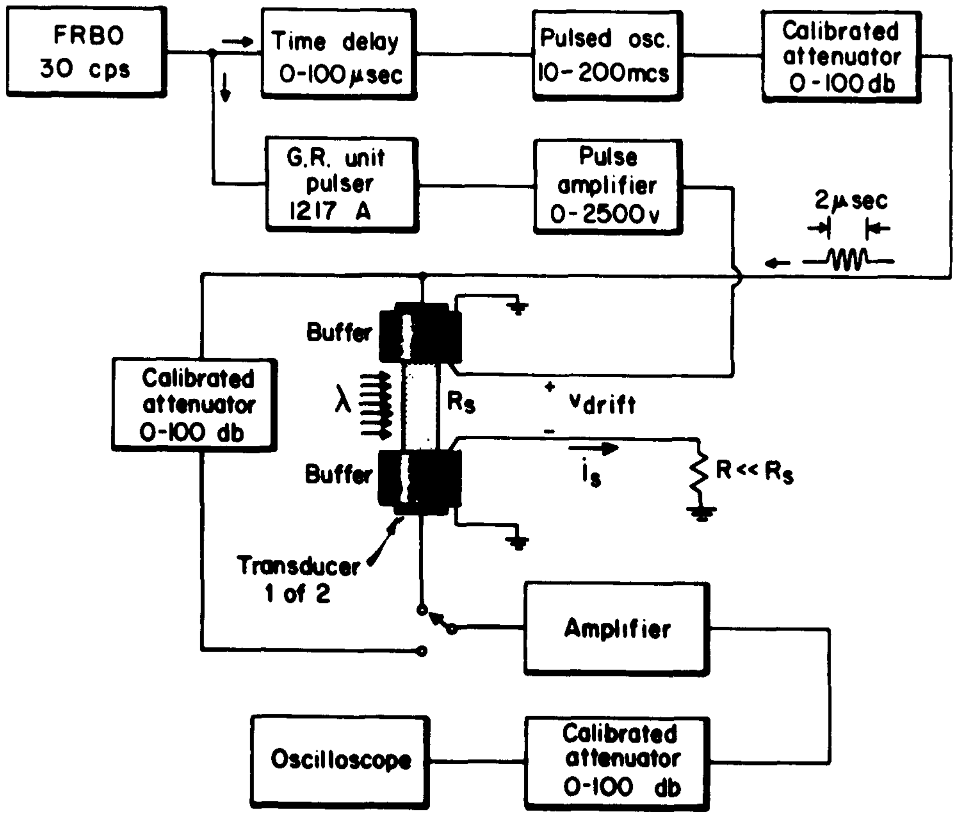

Fig. 2. Block diagram of experimental arrangement.

Due to heating problems with the high voltages used to drift the electrons, pulsed drift voltages were employed. Figure 2 shows the synchronization arrangement used to provide coincidence between the passage of the pulsed ultrasonic wave through the sample and the d-c drift of the electrons. As indicated, typical ultrasonic pulse lengths were 2 μsec. Transit time of the sample was 4 μsec.

Figure 3 shows the attenuation for the propagation of a transverse ultrasonic wave through a 7-mm length of CdS. The transverse (shear) wave travels in a direction perpendicular to the crystalline c axis of the sample.

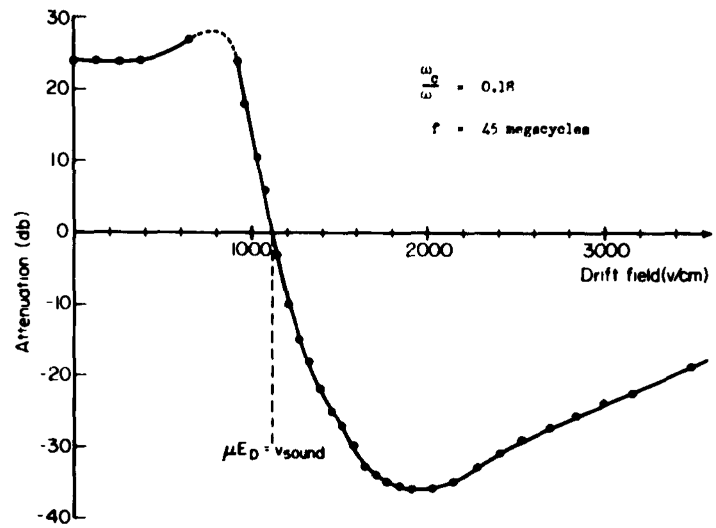

Fig. 3. Observed attenuation in 7-mm sample.

The pertinent piezoelectric constant that couples this shear wave to the electrons is e_{15}. Shear-wave was chosen in preference to longitudinal wave propagation because of its slower velocity. The importance of this consideration will become obvious in the next section. The zero of attenuation in Fig. 3 corresponds to the attenuation of the sample in the dark and is < 10 db for this sample. This figure shows a maximum negative attenuation or gain of 37 db for a 45-Mc ultrasonic signal propagating through the 7-mm length of sample with a drift field of about 1900 v/cm applied. The output signal power is about 10 milliwatts. The conductivity of the sample is $\sigma = 4.5 \times 10^{-5}\ [\text{ohm-cm}]^{-1}$.

B. One-Dimensional Treatment of the Wave Equation

The piezoelectric coupling effects on acoustic wave propagation can be effectively discussed in terms of a one-dimensional plane-wave model. Corresponding to the experimental arrangement, only an n-type semiconductor is considered. This treatment follows that of White.[10]

An ultrasonic plane wave propagating through a piezoelectric material is accompanied by a longitudinal electric field periodic with the displacement. In insulators, this piezoelectric field results in an additional contribution to the elastic constant. In a highly conducting medium the free carriers totally shield the piezoelectric field, and there is no piezoelectric contribution to the elastic constant. Midway between these extremes the elastic constant is dependent on the carrier concentration. Most of the discussion to follow will be concerned with this region. An analysis of the elastic properties of piezoelectric media for the three regions is now given.

The one-dimensional equations of state for a piezoelectric medium are

$$T = cS - eE, \tag{1}$$

$$D = eS + \epsilon E, \tag{2}$$

where T is the stress, S the strain, E the electric field, D the electric displacement, and c, e, and ϵ the elastic, piezoelectric, and dielectric constants, respectively. For the medium displacement, u, the one-dimensional wave equation is derived from the first of these

$$\frac{\partial T}{\partial x} = \rho \frac{\partial^2 u}{\partial t^2} = c \frac{\partial^2 u}{\partial x^2} - e \frac{\partial E}{\partial x}. \tag{3}$$

In an insulator the space charge Q is zero and, as a consequence of Gauss's law:

$$\frac{\partial D}{\partial x} = Q, \tag{4}$$

the spatially varying electric displacement is also zero. Used in conjunction with Eq. 2, the wave equation for a piezoelectric insulator becomes

$$\rho \frac{\partial^2 u}{\partial t^2} = c(1 + \frac{e^2}{\epsilon c}) \frac{\partial^2 u}{\partial x^2}. \tag{3'}$$

The term $e^2/\epsilon c$ is the piezoelectric contribution to the elastic stiffness in an insulator. For a highly conducting medium, the electric field in Eq. 1 is zero and there is no piezoelectric contribution to the elastic constant.

Intermediate between very high and very low conductivity, both D and E must be included in the propagation equation for the acoustic wave. This is the region of carrier concentrations appropriate to semiconductors. All further discussion will be restricted to this region. The expression for the current density J in an n-type semiconductor is given by

$$J = q\mu n_c E + qD_n \frac{\partial n_c}{\partial t} \quad , \tag{5}$$

where μ is the mobility of electrons, n_c the density of free electrons, and D_n the electron-diffusion constant. The charge continuity equation is

$$\frac{\partial J}{\partial x} = - \frac{\partial Q}{\partial t}. \tag{6}$$

The space charge Q can be written as

$$Q = -qn_s(x, t) \tag{7}$$

which permits n_c of Eq. 5 to be defined as

$$n_c = n_o + n_s(x, t). \tag{8}$$

To determine the modified elastic constant c', resulting from the piezoelectric term in Eqs. 1 and 3, Eqs. 4 to 8 are used to relate D, the electric displacement, and E, the electric field. Equation 2 is then used to eliminate D from the equations:

$$- \frac{\partial^2 D}{\partial x \, \partial t} = \mu \frac{\partial}{\partial x} \left[qn_o E - \frac{\partial D}{\partial x} E \right] - D_n \frac{\partial^3 D}{\partial x^3}. \tag{9}$$

For a small-signal (linearized) theory, the terms involving products of time-varying quantities are neglected. For the linearized equation, the form of the solution for E can be written as

$$E = E_o + E_1 \, e^{j(kx - \omega t)} \quad , \tag{10}$$

where E_o is a constant d-c field (the drift field) and E_1 the electric field accompanying the ultrasonic wave. The displacement of the medium is

$$u(x, t) = u \, e^{j(kx - \omega t)} . \tag{11}$$

Equation 9 now becomes

$$-\frac{\partial^2 D}{\partial x \partial t} = \mu q n_o \frac{\partial E_1}{\partial x} - E_o \mu \frac{\partial^2 D}{\partial x^2} - D_n \frac{\partial^3 D}{\partial x^3} \quad . \tag{9'}$$

Solving this equation, using Eqs. 10 and 2, gives a relationship between E_1 and u:

$$E_1 = u(-\frac{jke}{\epsilon}) \left\{ 1 - \frac{q\mu n_o}{j\omega\epsilon} \left[1 + \frac{\mu k}{\omega} E_o + jD_n (\frac{k}{\omega})^2 \right]^{-1} \right\}^{-1} . \tag{12}$$

Substituting Eq. 12 in Eq. 3 gives the modified elastic constant:

$$c' = c \left\{ 1 + \frac{e^2}{\epsilon c} \left[g(\omega, n_o, E_o) \right] \right\} . \tag{13}$$

The functional form of $g(\omega, n_o, E_o)$ is given by

$$g(\omega, n_o, E_o) = \left\{ 1 + \frac{jqn_o\mu}{\epsilon\omega} \left[1 + \frac{\mu k}{\omega} E_o + jD_n (\frac{k}{\omega})^2 \right]^{-1} \right\}^{-1} . \tag{14}$$

Now Eqs. 13, 11, and 3 provide an expression for the wave vector k:

$$\rho\omega^2 = c' k^2 , \tag{15}$$

where k has the form

$$jk = \alpha + j \frac{\omega}{v_s} . \tag{16}$$

The attenuation constant α is small ($|\alpha| \ll \omega/v_s$). Solving Eq. 15 for k is quite difficult unless approximations are made. Since $|\alpha| \ll \omega/v_s$, the substitution of $k = \omega/v_s$ in Eq. 14 is justified. This greatly simplifies the analysis, readily yielding expressions for the attenuation constant and the wave velocity. The following definitions will simplify notation:

$$\omega_c = \frac{q\mu n_o}{\epsilon} = \frac{\sigma}{\epsilon} \text{ the dielectric relation frequency,}$$

$$\omega_d = \frac{v_s^2}{D_n} \text{ the "diffusion" frequency,}$$

$$\gamma = 1 - \frac{\mu E_o}{v_s},$$

$$K^2 = \frac{\frac{e^2}{\epsilon c}}{1 + \frac{e^2}{\epsilon c}} \simeq \frac{e^2}{\epsilon c} = \text{electromechanical coupling coefficient ,}$$

σ = average conductivity.

The electromechanical coupling factor is typically very small (K^2 = 0.04 for CdS); the approximation of $K^2 = e^2/\epsilon c$ is therefore well justified. Under these approximations the expressions for c', α, and v_s are, respectively,

$$c' = c\left[1 + K^2 \frac{\gamma + j\frac{\omega}{\omega_d}}{\gamma + j\frac{\omega}{\omega_d} + j\frac{\omega_c}{\omega}}\right] ; \tag{17}$$

$$\alpha = \frac{K^2\omega_c}{2v_s\gamma}\left[1 + \frac{\omega_c^2}{\gamma^2\omega^2}\left(1 + \frac{\omega^2}{\omega_c\omega_d}\right)^2\right]^{-1} ; \tag{18}$$

$$v_s = \sqrt{\frac{c}{\rho}}\left[1 + \frac{K^2}{2}\frac{1 + \frac{\omega_c}{\gamma^2\omega_d} + \frac{\omega^2}{\omega_d^2\gamma^2}}{1 + \frac{\omega_c^2}{\gamma^2\omega^2}\left(1 + \frac{\omega^2}{\omega_c\omega_d}\right)^2}\right] . \tag{19}$$

The expressions for the time-dependent part of the current, the electric field, and the space charge as determined from Eqs. 5, 7, and 12 are .

$$J_1 = \sigma E_1\left(\gamma + j\frac{\omega}{\omega_d}\right)^{-1} = -\frac{\sigma e}{\epsilon} S\left(\gamma + j\frac{\omega_c}{\omega} + j\frac{\omega}{\omega_d}\right)^{-1} , \tag{20}$$

$$E_1 = -\frac{e}{\epsilon} S \frac{\gamma + j\frac{\omega}{\omega_d}}{\gamma + j\frac{\omega}{\omega_d} + j\frac{\omega_c}{\omega}} , \tag{21}$$

$$n_s = -\frac{\sigma}{qv_s} E_1\left(\gamma + j\frac{\omega}{\omega_d}\right)^{-1} = \frac{\omega_c e}{qv_s} S\left(\gamma + j\frac{\omega_c}{\omega} + j\frac{\omega}{\omega_d}\right)^{-1} . \tag{22}$$

C. The Interaction Mechanism

The periodic electric field accompanying an ultrasonic wave in a piezoelectric semiconductor causes currents to flow, producing a periodic space charge and hence a spatially varying conductivity. If a d-c field is applied to drift the carriers parallel to the ultrasonic wave at sound velocity, there will be no currents flowing relative to the periodic electric field accompanying the ultrasonic wave. Thus this electric field cannot couple energy to the electrons and the ultrasonic wave producing this electric field cannot be attenuated. The only attenuation mechanism being considered here is that due to piezoelectric coupling of the ultrasonic wave with the electron system. If the electrons drift with a velocity less than that of sound, the charge will flow relative to the electric field of the ultrasonic wave. This current has a component in phase with the electric field, resulting in loss of acoustic energy from the wave because of Joule heating. For electron-drift velocities greater than sound velocity, the current has a component 180 degrees out of phase with the electric field, resulting in energy being transferred from the drifting electron stream to the ultrasonic wave. There are, in effect, two identifiable components of the electric field accompanying the wave: the electric field of piezoelectric origin and another due to a direct current passing through a medium whose conductivity is spatially varying due to the presence of the ultrasonic wave. When the electrons are drifting faster than the ultrasonic wave, these two components give a resultant electric field which is 180 degrees out of phase with the current.

The results given by Eq. 18 correlate reasonably well with experimental results (Fig. 4). For the theoretical curve, the following values have been used: $\omega/2\pi$ = 45 Mc, $\omega_d = 5 \times 10^9$ radians/sec, $\omega_c/\omega = 0.18$, μ = 165 cm^2/volt-sec, $K^2/2 = 0.02$, and $v_s = 1.75 \times 10^5$ cm/sec.

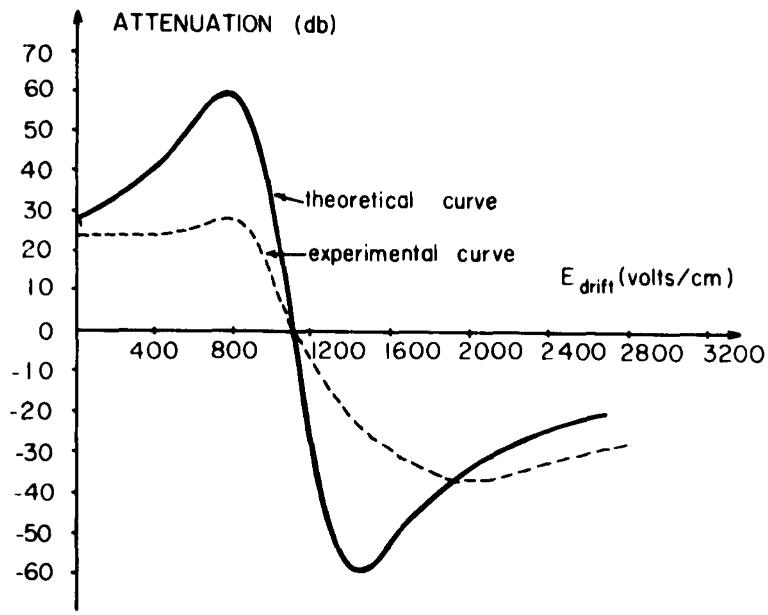

Fig. 4.

Comparison of experimental and theoretical attenuation in 7-mm CdS sample.

Several explanations can be offered for the discrepancy between experimental and theoretical curves. Probably the most important source of error is the inhomogeneous sample conductivity due to nonuniform illumination by the sodium lamp. This results in different electron-drift velocities for the various regions of the sample and tends to smooth out the attenuation peaks predicted by theory.

II. Acoustoelectric Effect

A. Experimental Results and Discussion

Figures 5 and 6 show the impressed voltage and the resulting current passing through a 7-mm sample of CdS. Figure 7 is the ultrasonic signal measured by a 50-Mc quartz transducer so arranged as to receive shear waves propagating parallel to the current flow. The current decreases after about 15 μsec while the voltage through the sample remains constant. After about 25 μsec an ultrasonic signal is obvious at the transducer. This signal

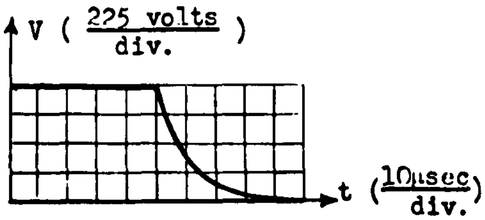

Fig. 5. Sample voltage versus time.

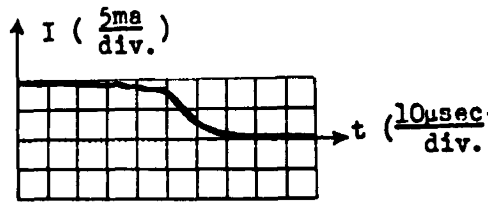

Fig. 6. Sample current versus time.

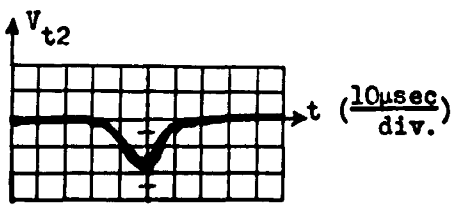

Fig. 7. Ultrasonic signal at transducer versus time.

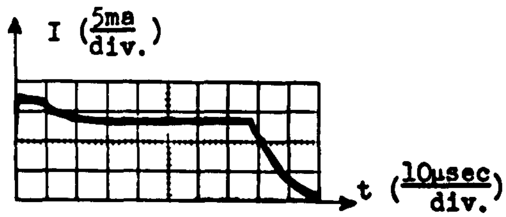

Fig. 8. Sample current versus time.

increases in amplitude until the current attains a steady value at some current lower than that attained in the initial 15-μsec period. Both the current and the ultrasonic signal saturate after a time dependent on the voltage applied. This saturation is obvious after only 20 μsec in Fig. 8, where the sample voltage is twice that of Fig. 5.

Smith[12)] observed a "kink" in the I-V characteristics of CdS and GaAs for fields of about 1600 and 80 volts/cm, respectively. Above this kink the sample resistance increased markedly. Although suspicious that acoustic flux buildup was responsible, Smith was unable to obtain evidence of such a buildup. Figure 7 is presented here as evidence that it exists. The change in resistance is obvious by the difference in sample current before and after the flux builds up while a constant voltage is applied.

The decrease in current can be explained quite readily by considering the results of the preceding section. The kink only occurs for voltages greater than that corresponding to an electron-drift velocity equal to sound velocity. The 1600-volts/cm field of Smith corresponds to the region of large negative attenuation given by Fig. 3. At voltages in this "gain" region, the shear modes of the lattice vibrations are amplified and take energy from the drifting carriers. These modes build up and are detected as the ultrasonic signal of Fig. 7. The lattice waves being amplified may be described in terms of plane waves at various frequencies. Each of them carries an energy W and, associated with it, a momentum p given by p = W/c, where c is the wave velocity. Considering only energy-exchange mechanisms between these waves and the carriers via the piezoelectric coupling leads to the following somewhat simplified description: If a lattice wave absorbs energy from the electron stream, it must also absorb momentum, for the two are intimately related by p = W/c. Since the waves which are being amplified run only along the direction of the carrier stream, the momentum absorption will also be in this direction.

The applied electric field supplies momentum to the carriers according to the familiar relation

$$q\vec{E} = h\frac{d\vec{k}}{dt} = \frac{d\vec{p}}{dt} \quad , \tag{23}$$

while the lattice waves absorb momentum according to

$$\frac{d}{dt}\ \frac{\langle W\rangle}{c} = \frac{dp}{dt}_{\text{lattice waves}} \tag{24}$$

This picture is incomplete without a discussion of the effect of the carrier drag exerted by a wave that has been reflected from the end of the sample and is traveling against the carrier stream and hence being attenuated. Such a wave loses energy and thus momentum in a direction opposite to that of the current. The carriers must therefore gain momentum in this direction. This corresponds to a decrease in momentum in the direction of carrier flow, or in other words a decrease in current. Thus when the voltage is sufficient to drift the carriers faster than the speed of sound, all lattice waves, whether traveling with the stream and being amplified or against it and being attenuated, contribute to a decrease in the current and an apparent increase in resistance.

Figure 8 indicates a saturation of acoustic flux when the current reaches a steady value following the decrease due to the buildup of flux. A nonlinear mechanism that explains the acoustic flux saturation stands as one of the major areas for further investigations.

B. Theoretical Explanation

Clearly a linear theory cannot explain the wave-particle drag, for the effect involves the conversion of energy from a high-frequency wave to a zero-frequency current. In the derivation of the expression for the attenuation constant α, all nonlinear effects were neglected. In particular in the expression for the current

$$J = q\mu_n \left[n_o + n_s(x,t)\right]\left[E_o + E_1(x,t)\right] + qD_n \frac{\partial n_c}{\partial t} \qquad (25)$$

the product terms of $n_s(x,t)$ and $E_1(x,t)$ were neglected. It is just these terms that result in the acoustoelectric current:[13)]

$$J_{AE} = \mu q\, n_s E_1 = \text{acoustoelectric current.} \qquad (26)$$

Using the expressions for n_s and E_1 derived earlier from the linear theory, and limiting the treatment to a single-frequency ultrasonic wave, this expression becomes

$$J_{AE} = \mu c \alpha S^2 \left[1 + \cos(2kx - 2\omega t + 2\varphi)\right],$$
$$\varphi = \tan^{-1} -\left(\frac{\omega_c}{\gamma\omega}\right). \qquad (27)$$

The acoustoelectric current has the same sign as the attenuation constant previously derived. Experimentally, acoustoelectric currents corresponding to nearly total bunching of the carriers, $n_s \simeq n_o$, were observed.

To indicate the validity of the expression given in Eq. 27 for the acoustoelectric current in terms of the strain, S, this current was measured as a function of the amplitude of the incident strain. The strain generated by the input transducer as a function of the acoustoelectric current is given in Fig. 9. Equation 27 predicts a slope of 2 for the logarithm of the acoustoelectric current vs. the logarithm of the input-strain amplitude. The agreement of a large part of the experimental curve with the theoretical curve is quite reasonable, giving support to Eqs. 26 and 27.

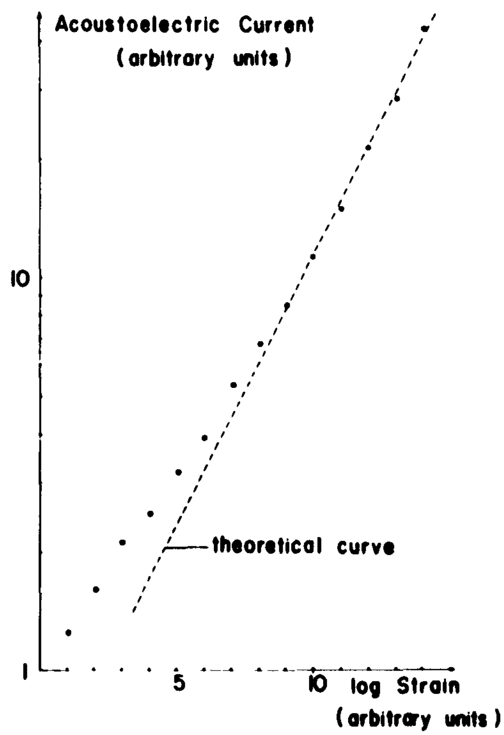

Fig. 9.

Acoustoelectric current dependence on input strain.

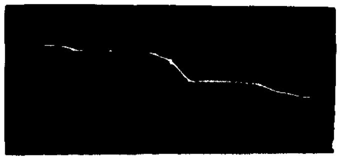

Fig. 10. Sample current vs. time ($\omega_c/\omega = 0.18$; f=45 Mc). (I_s↑ 2-ma division; t → 2-μsec division.)

Fig. 11. Quarter-watt 45-Mc wave introduced.

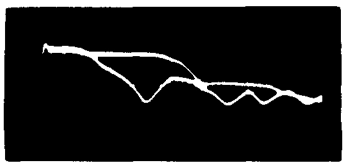

Fig. 12. Half-watt 45-Mc wave introduced.

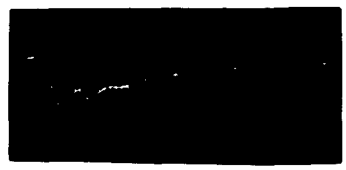

Fig. 13. Acoustoelectric voltage vs. time (V↑1-volt division; t →5-μsec division).

Fig. 14. Acoustoelectric current vs. time (I↑100-μamp division; t → 5-μsec division).

Figures 10, 11, and 12 show the current through the CdS sample for a voltage in the high negative attenuation region. The current in all three figures exhibits an acoustoelectric "wiggle" due to the buildup of acoustic modes initially excited by the sudden application of the drift voltage. Figures 11 and 12 also show the effect of introducing into the sample an external 45-Mc signal of about 1/4 and 1/2 watt power, respectively. This signal absorbs a large amount of momentum from the carriers as it passes back and forth through the sample, thereby decreasing the current. This further supports the acoustoelectric theory of Smith's "kink" in piezoelectric semiconductors.

Figures 13 and 14 show the voltage and the current, respectively, of the sample resulting solely from the attenuation of an ultrasonic wave passing through the sample. At t = 3 microseconds an ultrasonic wave of about 1/2 watt power enters the sample. A 100-picofarad capacitor is connected across the sample, resulting in the pulsed current of Fig. 14 whenever the voltage of Fig. 13 rises rapidly. The several pulses result from the subsequent entrance into the sample of that part of the ultrasonic wave which has been multiply reflected in the buffer rods. The time constant of the voltage decay corresponds approximately to the sample resistance and the 100-picofarad capacitor.

Conclusions

Several effects resulting from the coupling of free electrons and a piezoelectric lattice have been studied. Part I was concerned with the effect of free electrons on the elastic properties of the material. The ultrasonic wave amplification observed here is almost identical to the observations published by Hutson, McFee, and White.[9)] Part II was concerned with an explanation of the "kink" observed by Smith[12)] in the I-V characteristics of piezoelectric semiconductors. The suggestion that acoustic flux was responsible for the kink was given by Smith but he was unable to confirm this experimentally. Hutson[13)] suggested that the source of the kink was the acoustoelectric effect; the theoretical explanation given here follows his work. Experimental observations which confirm the acoustoelectric explanation are reported.

The most obvious general conclusion to be reached from the observations made is that the consequences of piezoelectric coupling can have a significant effect on the properties of piezoelectric semiconductors. In particular, the electrical properties of CdS, ZnO, CdSe, and GaAs can be strongly altered as a result of acoustic flux.

One of the more promising areas of study of the piezoelectric coupling mechanism is the realm of nonlinear effects. As mentioned in Part II, a nonlinear mechanism is responsible for the acoustic flux saturation discussed in conjunction with Fig. 8. Work is continuing on some of these effects, especially those responsible for phonon-phonon interactions.

An explanation of phonon-phonon scattering usually considers only the effect of anharmonic lattice forces in producing the interaction between the lattice waves. We suggest that the piezoelectric coupling of the electron and lattice systems makes possible an observable phonon-phonon scattering. This interaction is a consequence of the nonhomogeneous elastic constant resulting from the presence of space charge and takes place with perfectly harmonic lattice forces. As seen in the analysis of Eq. 17, the elastic constant is simply related to the conductivity. Since a lattice wave in a piezoelectric semiconductor bunches charges periodic with the material displacement, it creates a spatially periodic elastic constant. Another lattice wave piezoelectrically coupled to this charge will encounter this periodic elastic constant and will be scattered, as if from a diffraction grating. Thus it should be possible to observe a third lattice wave resulting from the interaction of two waves introduced into a piezoelectric semiconductor.

Note added in proof

Following the completion of this work, McFee[14)] has published observations of the acoustic flux buildup coincident with the kink in the I-V characteristics of CdS. His results are in substantial agreement with ours. He reported a decrease in the amplification of an externally introduced ultrasonic wave in the presence of high acoustic flux. We have also observed this

14) J. H. McFee, J. Appl. Phys. 34, 1548 (1963).

effect and ascribe it to the phonon-phonon-interaction mechanism mentioned above. The externally introduced wave interacts with the acoustic flux, scattering the ultrasonic energy to higher frequencies.

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